Chapter 6

Measurements with high resolution spectrometer

OMA Spectrometer. Measures visible spectrum 300 nm to 670nm. This allows diagnosis of the light emitted by impurity species within the trailing plasma. Two modes of operation are possible. We can integrate over the entire shot, or gate the spectrometer to measure light from a small time interval within the shot. Time evolution of spectrum during the acceleration process can be built up over a sequence of shots in the gated mode by stepping the delay time of the start of the spectrometer gate pulse relative to the time of CT plasma formation. The spectrometer can view the plasma axially via an internal mirror, or transversely through glass window ports. Focusing optics are required for time-gated operation in order to collect enough light into the fiber optic bundle to make detectable light signal at the diffraction plane. [figure of low res OMA time evolution]

A transmission grating spectrometer appropriate for visible light (3500 Åto 6800 Å) was built by Alex Graf[1] in collaboration with EBIT group and was used to study the plasma created by the CTIX machine. The fast time resolution and high spectral resolution are possible due to special

[1]Graduate student in UCD Physics Dept.

LLNL fabricated transmission gratings, which the design is based around.

The transmission grating is circular with a diameter 150 mm, groove spacing of 3944.5 +/- 0.5 Å. Due to its large diameter this grating allows faster integration times, it has an f/3 which is much greater than the f/10 in a conventional spectrometer. It has a demonstrated spectral resolution, $\lambda/\Delta\lambda$, of up to 14500 for a wavelength of 5790.7 Åwhile using a 50 μm slit (Fig. 1 and 2). The optics within the spectrometer allow for off axis ($\pm$ 1 cm) input light. [figure 2 = schematic of spectrometer] [ref RSI paper]

My part in the spectrometer project was primarily the development of practical implementations of fast detector arrangements suitable for viewing the CTIX plasma. We constructed a sequence of custom-made adjustable supports for mounting any available fast CCD camera that we had at our disposal into the interior of the spectrometer so that it could record the spectrum image at the dispersion plane. All together, we took data using a sequence of 5 distinct detectors in as many months of run time.

The first experimental task that we completed was a time integrated impurity survey of the light from a helium CT plasma. The spectral resolution is far superior to that of the former device allowing a proper separation and identification of the many features present. This high-resolution survey spectrum spanned most of the visible wavelengths from 3500 Åto 6800 Å. This spectrum was compiled from about 50 individual spectra, and it mapped out the location and relative intensities of hundreds of impurity lines, as well as the primary helium and hydrogen lines. Next we selected the one of the brighter spectral lines for further study. The best candidate was the line transition at 4686 Åof singly charged Helium (He II)

[Graph of line at 4686]

The largest shift expected for a 200 km/s CT is around 4 Åwell within the spectral bandwidth of typically 150 Å, while the smallest shift we can detect is at least $\sim$ 0.4 Å(less if the light is sufficiently bright).

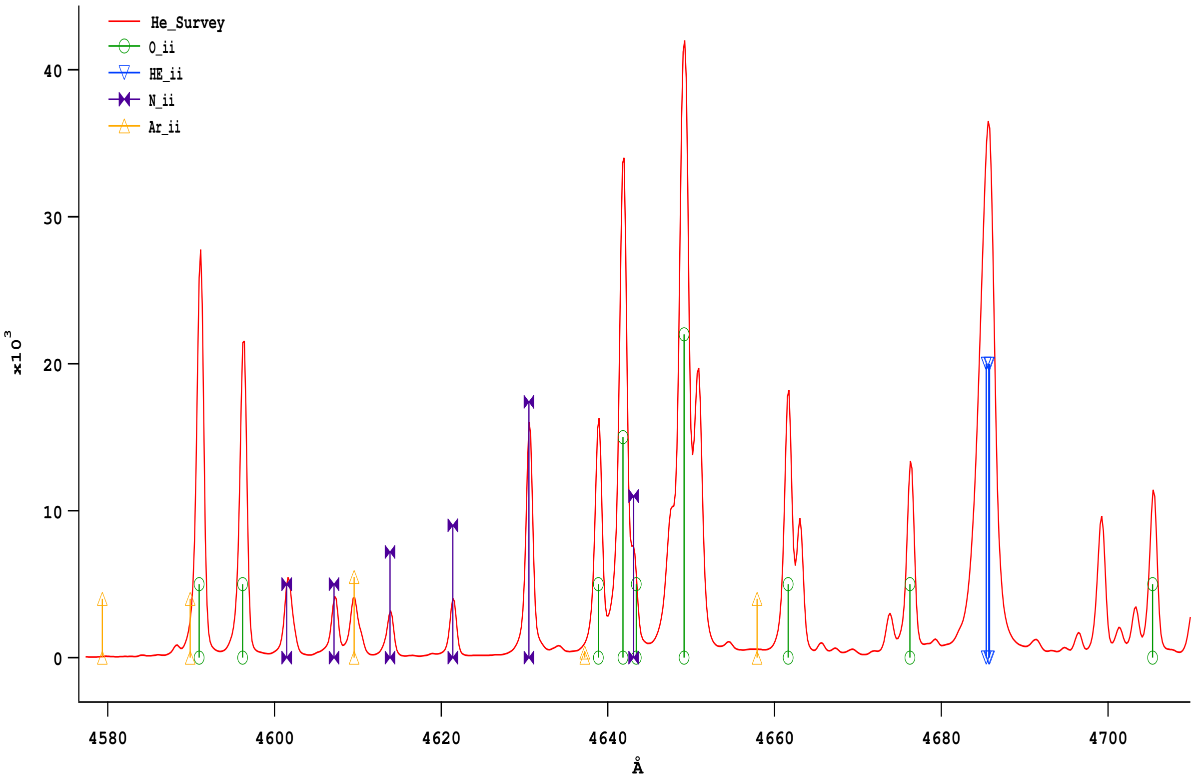

Figure 6.1: Survey spectrum of Helium plasma near He II line

We measured Doppler shifts of this line using an axial line of sight, where the plasma is rapidly moving toward the point of observation. We compared this to spectra that were taken along three different transverse chords that are orthogonal to the direction of plasma motion and so experience no Doppler shift. The spectra along all four of these lines of sight were taking using a time gating method that mapped out the time evolution of the spectral lines and their Doppler shifts in 1 microsecond increments from the moment of plasma breakdown until 30 microseconds after breakdown. During this period the acceleration of the CTIX plasma from 0 to 200 km/s occurs.

The resulting time evolution of Doppler measured plasma velocity was a bit of a surprise at first. Using time gating of the CCD we are able to watch the evolution of ion velocity using the measured Doppler shift at each time step. He II ion velocity peaks very early at 1.5 ms, with a

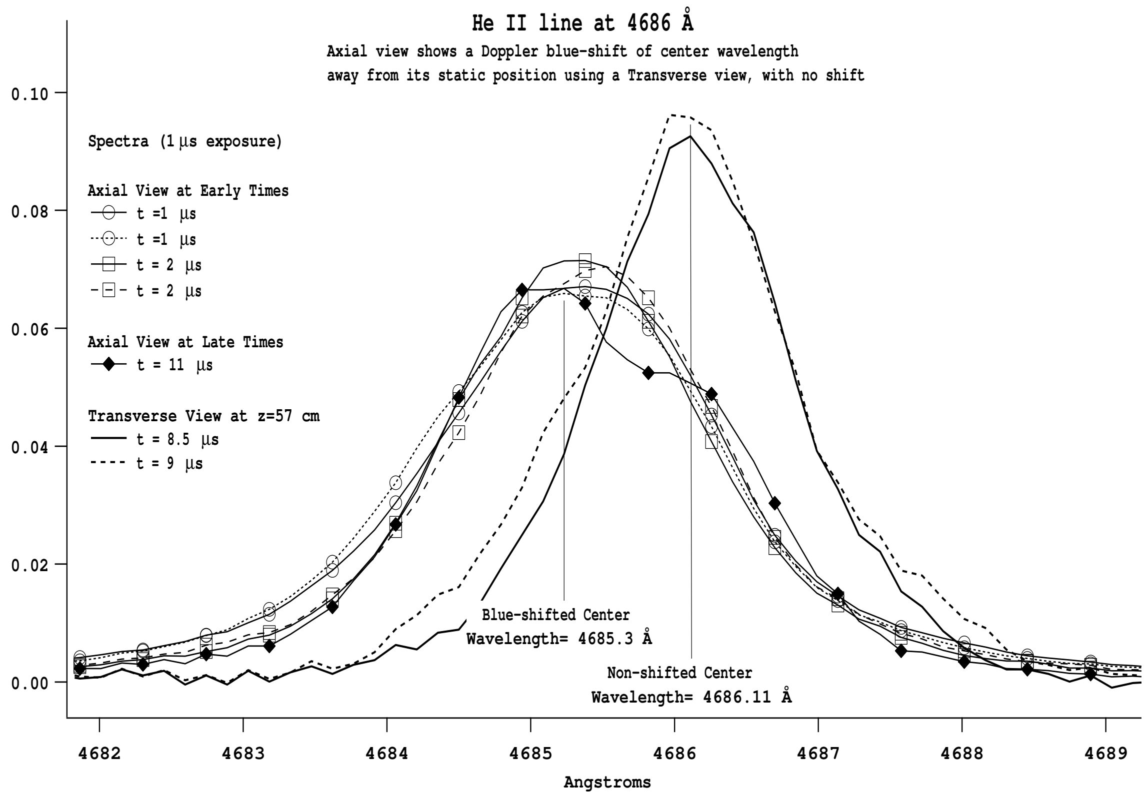

Figure 6.2: Survey spectrum of Helium plasma near He II line

maximum of ∼50 km/s and then dwindles to only 10 km/s during most of the acceleration of the compact toroid. A second peak of ∼72 km/s occurs at 14 ms, which is coincident with the moment when the CT leave the end of the accelerator, at this time a re-strike occurs at z = (0 to 20 cm) due to the ringing of the railgun circuit.

We never saw the plasma reach anything close to the peak velocity of 200 km/s as measured by the time of flight between magnetic probes. And the velocity as a function of time with its double hump shape seemed peculiar.

Why?

6.1 Doppler measurements of plasma velocity

General scope of work. A self-confined, magnetized plasma ring called a Compact Toroid (CT) is accelerated up to speeds of 200 km/s by the CTIX accelerator. Experimental work has been done on CTIX using a high-resolution transmission grating spectrometer, on loan from the EBIT group.

Bound state line spectra of the plasma have been measured that allow identification of plasma impurities and determination of ion velocity during the acceleration process. Doppler shifts of Helium, Argon, Nitrogen, and Oxygen have been measured.

Here we focus on the Helium data. One key practical result is that the fast rate of ionization imposes a limitation to the size of the region where Doppler measurements can be made. The helium data we have gathered shows a dramatic variation of ion density as a function of position and time, which can be accurately modeled within a simple framework.

Survey of visible emission (3650 Åto 6750 Å) Detected Oxygen, Nitrogen, Argon and Carbon, occurring in Z = 0, 1, 2 charge states. We ran with Helium as the primary gas in order to measure large Doppler shifts

6.2 Measurement of Average Doppler Velocity

We are looking at a comparison between the transverse spectra and the axial spectra of the line emission of He II (Z=1) at $\lambda = 4686$ Å.

The transverse spectra have no shift, while the axial spectra show a Doppler blue-shift because the plasma is moving rapidly toward the input fiber. The apparent wavelength of the blue-shifted light is:

$$\lambda = \lambda_0(1 - v/c)$$

where v/c is the ratio of the ion velocity to the speed of light, which is always less than 10^{-4} for the CTIX plasma. Experimentally however, we can not measure the Doppler shift of individual ions. In

our setup, the light from nearly all the ions in the entire volume of plasma is collected by the axial line-of-sight fiber optic. The measured shift in center wavelength is actually a weighted average of the Doppler shift throughout the vessel. And so we can only infer an average fluid velocity based on this average Doppler shifted wavelength.

$$v_{ave}(t) = c\left(1 - \frac{\lambda_{ave}(t)}{\lambda_0}\right) \tag{6.1}$$

where $\lambda_{ave}(t)$ is the experimental average of Doppler shifted center wavelength as measured by the axial line of sight and λ_0 is the unshifted center wavelength of the line emission as determined by the transverse measurements. $\lambda_{ave}(t)$ is found by taking the first moment of the measured line profile.

$$\lambda_{ave}(t) = \frac{1}{N_I(t)} \int_{\lambda_0-\Delta}^{\lambda_0+\Delta} \lambda I(\lambda,t)d\lambda$$

where the normalization of single line of the spectrum at each instant in time is given by

$$N_I(t) = \int_{\lambda_0-\Delta}^{\lambda_0+\Delta} I(\lambda,t)d\lambda$$

Here, $I(\lambda,t)$ is the output signal of the spectrometer when viewing the axial line of sight, calibrated for wavelength but with intensity in arbitrary units. If we assume a Gaussian line shape for emission from an infinitesimal fluid element we can approximate the spectrum as the integral over the axial coordinate z over the length of the accelerator L

$$I(\lambda,t) = \frac{1}{\sigma\sqrt{\pi}} \int_0^L I(z,t)e^{-(\lambda-\lambda_0(1-v(z,t)/c))^2/\sigma^2} dz \tag{6.2}$$

where $I(z,t)$ is the intensity of emission at the center wavelength from the fluid element at position z and time t, and σ is the line width. Here $v(z,t)$ denotes the actual fluid velocity of the plasma, which varies in time and position throughout the accelerator. The velocity function of the plasma is not known for all (z,t) but it is strongly constrained by measurements of the average

velocity determined by the time of flight between signals of magnetic probes at three axial positions along the acceleration section.

Also, the results of 2-D MHD simulation of the accelerator dynamics of CTIX provide accurate approximations to $v(z,t)$. However, one of the goals of this spectroscopic work is to find an independent measure of $v(z,t)$ that can be compared to other results as a check of accuracy. Using the above expression for $I(\lambda,t)$ we can evaluate $v_{ave}(t)$. After some simplification we find

$$v_{ave}(t) = \frac{1}{N_I(t)} \int_0^L I(z,t)v(z,t)dz \tag{6.3}$$

The emission intensity $I(z,t)$ is of key importance. We have endeavored to measure it as directly as possible with the use of narrow bandpass filtered photomultiplier tube measurements made simultaneously at several positions along the length of the accelerator. These measurements can be analyzed using the Lagrangian interpolation technique, in synthesis with the magnetic field data. Additionally, our understanding of the basic ionization and excitation mechanisms can be used to make a simple predictive model of the accelerated helium ions in our system. Ultimately we would like to compare the average velocity evolution measured via Doppler spectroscopy to the results from the two other independent methods, the PMT-Magnetic composite of $I(z,t)$ the yields $v_{ave}(t)$, and a purely theoretic approach.

In the light of this possible cross-comparison of methods, the geometric complication of the axial integrated data is ultimately a good thing since it means that the Doppler measurements provide some constraints on a model of $n_i(z,t)$, which up to this point had been uncharted on the CTIX device.

Ion Velocity Evolution

Using time gating of the CCD we are able to watch the evolution of the average ion velocity using the measured Dopplershift at each time step. Talk about specifics of time gating This analysis

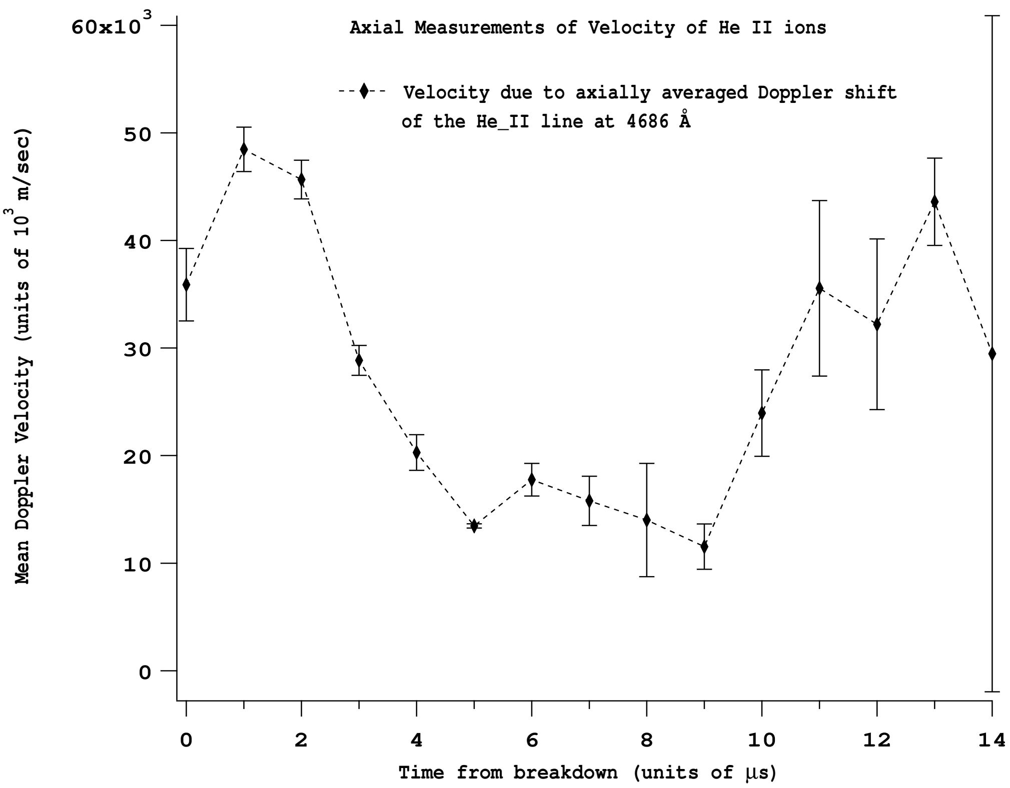

Figure 6.3: Average Doppler velocity as a function of time

shows that He II ion velocity peaks very early at 1.5 μs, with a maximum of $\sim$ 50 km/s and then dwindles to only 10 km/s during most of the acceleration of the compact toroid. This unusual result requires some further explanation. Careful examination of the transverse data show that the He II state becomes extinct as it propagates down the accelerator. Very little is observed at the z = 91 cm, and absolutely none at all is seen at z = 142 cm.A second peak of $\sim$ 72 km/s occurs at 14 μs, which is coincident with the moment that the CT becomes fully detached from the end of the accelerator, at this time a re-strike occurs in the formation section $(0 < z < 20cm)$ due to the ringing of the rail-gun circuit.It is clear that the maximum velocity measured by the Doppler spectrometer is much less than the CT velocity of 200 km/s as measured by the magnetic probes. The reason for this discrepancy is all in equation 6.8. We have come to understand that because the electron

temperature is sufficiently hot, the population of He II does not last more than a few microseconds during the discharge before it becomes fully ionized. Also He II is also limited in space to the region close to the formation section, because by the time a He II ion gets to the end of the accelerator it has had enough time to turn into an α particle. And so the Doppler spectrometer using the axial line of sight to view the plasma will never see He II ions moving at the maximum plasma velocity. It can only observe them earlyon in the acceleration process, when velocities are small. The helium ions do in fact get up to the high speeds of 200 km/s or higher, we just can't see them once they loose their last electron. This is a very reasonable interpretation of the data, however it is important to carefully compare the timescales involved in the ionization and acceleration processes and make sure the numbers work out. In the next section we investigate several models and compare them to experimental results.

6.3 Photomultiplier tube measurements

When a charge state is being depleted during the acceleration process, there will be some diminishment of its light emission with increasing axial position. Fast photodiodes with low-noise RF amplifiers were used to measure visible light emissions from the CTIX plasma. The light output of the three accelerator ports, as well as the axial line of sight were monitored in this way.

Optical band-pass filters were used to isolate the light from distinct impurity species and find its evolution as a function of axial position and time. The most general observation we can take away from the photodiode measurements is that across the spectrum, all visible emission was decreasing exponential with increasing axial position. We believe this is primarily due to thermal electron impact ionization.

I was involved in the task of using the results from the high resolution survey spectrum to select a set of optical bandpass filters that allowed light from a limited region (10 nm wide) of the plasma spectrum to be measured by amplified silicon photodiodes. A summer student, Michael

??? from the National Undergraduate Fellowship for Plasma Research constructed three amplified photodiode assemblies with moderate width (10 nm)optical bandpass filters and measured the time evolution of light at the three diagnostic windows along the accelerator section. The visible emission was measured at wavelengths of 465 nm (includes He II, OII, NII), 435 nm (includes OII) and 655nm (includes Hα line). For comparison, the total visible light emission was measured without the use of filters.

These measurements gave some circumstantial evidence that the ionization model I proposed was correct. However, they had the problem that the filters took in light from a variety of different line transitions, and so it was not possible to isolate exactly what the He II line at 468.6 nm was doing.

Three quantities were examined in the analysis of this data. First, the time of arrival of the peak signal was used to compare the kinematics of the compact toroid magnetic field and the region of visible light emission. Second, the time difference between the arrival of the peak signal of the filtered light and other signals. Used to look for any separation of ion species in the tail, as the various masses of each might lead to slightly differing acceleration. This was primarily done to test a hypothesized effect of different mass ions becoming separated by the acceleration, similar to a centrifuge. Lastly, the ratio of signal from the filtered photodiode to the unfiltered photodiode, over the duration of each shot. This was used to track the time evolution of atomic processes such as ionization and scrape-off.

Once I began working with the narrow filters, I ran into a number of technical complications that we had not encountered with the wide filters. Initially I had simply plugged the narrow filters into the original photodiode housing, but that suffered from the serious problem that light plasma could enter the filter at all angles from 0 degrees to as large as 30 degrees off of normal incidence.

The critical effect is that the center wavelength of the transmission curve becomes shifted with increasing angle. So non-helium light from neighboring spectral lines could still get through

the filter if they enter at some significant angle. To solve this, I first quantified this effect and found that there is a shift of the center wavelength by approximately 0.1 nm per degree away from normal.

Based on the survey spectra there were neighboring oxygen lines about 0.5 nm on either side of the He II line so we would need to limit the angular acceptance to well below 5 degrees. This has been accomplished with the construction of 9 cm diameter collimator tubes that have a pair of adjustable apertures separated by 55 cm, and internal baffles that block internal reflections.

The narrow bandpass filters are mounted in micrometer adjustable universal joint swivel mounts that allow precise alignment of the plane of the filter to be exactly perpendicular to the axis of the aperture pair. The apertures can be varied in size to optimize the trade-off between angular acceptance and light signal level.

Under typical plasma conditions the angular acceptance can be limited to less than half a degree, while still allowing good light signal.However, many orders of magnitude of the plasma light are thrown away when using the combination of the collimator and the narrow bandpass filter. The resulting light signal was far too dim to be detected by the original silicon photodiode and amplifier circuit. A much more appropriate choice of detector is a photomultiplier tube (PMT). They have nanosecond response times and can be sensitive enough to count single photons. We happened to have an old RCA model 8852 PMT and I was able to borrow two more of the same model from the SSPX group.

[figures showing PD signals as a function of z (logplot)]

As the CT moves down the accelerator it emits less and less light.Fast Photodiode measurements show an exponential decrease of: Total visible light Emission near 465 nm (includes He II, OII, NII) Emission near 435 nm(includes Oxygen II) Emission near 655nm (includes H a line)

6.4 Ionization model

Closed Constant Temperature Ionization Model At the instant of plasma formation there is already a large cloud of moderately high density neutral helium filling the formation section and diffusing lightly out into the accelerator section. Once a small population of energetic electrons becomes liberated within the static electric field, ionization of the neutral proceeds rapidly and the electron and ion densities rise primarily through the process of single electron impact ionization. Figure 2 diagrams the excitation and ionization process that occurs in the CTIX helium plasma. Because the excitation and ionization energies are comparable, if the plasma electron population is hot enough to cause visible line emission from a species, then it also has enough energy to ionize that species into the next higher charge state. It happens that the $\lambda = 4686$ line of He II is one of the brighter lines in the plasma. Its brightness is good for visible spectroscopy because it allows short integration times, however the high magnitude of brightness also means that He II very rapidly becomes fully ionized long before the experiment is over, making it impossible to observe the maximum velocity of the CT via Doppler shifted line emission.[figure 2 = diagram of excitation and ionization process]Electron Temperature Probe measurements show an Electron temperature of $T_e = 54$ eV Electron temperature of $T_e = 54$ eV is high enough to rapidly burn through neutrals and singly charged ions leaving only an αparticle plasma that does not emit in the visible.

[figure of electron energy distribution function] comparison of cross sections Recombination rates are small ($a \sim 10^{-14} cm^3 s^{-1}$) Ions will not recombine before the experiment is over ($25 \mu s$) because the lifetime of ions (before they recombine) is $1/(a\ n_e) \sim 1$ second. therefore..

Ionization fraction of the plasma is a monotonically increasing function of time.

The rate of double ionization due to electron impact is more than an order of magnitude smaller than for single ionization, and does not have a significant effect on the lifetime of the He II in the CTIX plasma. First, He II can only loose one more electron before it is fully ionized, so double ionization does not affect He II at all once it has formed. Second, the small effect that

does exist acts primarily to slightly reduce the maximum value of He II density that is obtained during the evolution by allowing a small fraction of the Helium neutrals to bypass the He II state and go straight to the fully ionized state. This does not significantly affect the lifetime of the He II population, and so double electron impact ionization will be ignored. Photo ionization rate?

Formation Region Model In the formation region, where the neutral density is high, the evolution of $n_0(t)$ and $n_i(t)$ are coupled through two first order nonlinear ODE's and an algebraic equation for $n_e(t)$. The density functions can be formulated in terms of the constant $N = n_0(-\infty)$ which is the number density of neutrals before any ionization takes place.

At time $t = 0$ the initial conditions are $n_0(0) = N(1-\epsilon)$, $n_i(0) = n_e(0) = N\epsilon$ where ϵ is a number much less than one. This model is closed in that no particles enter or leave the volume. However, if we assume that the ionization rates S_0 and S_i (for neutrals and singly charged ions respectively) to be constant in time then some large amount of energy must enter the system to keep the electron temperature constant.

If it is desired, the doubly charged ion density (α -particle density) canbe can be easily accounted for using conservation of nucleons once $n_0(t)$ and $n_i(t)$ are found. The evolution equations are:

$$\frac{dn_0}{dt} = -S_0 n_e n_0 \qquad \frac{dn_i}{dt} = -S_i n_e n_i + S_0 n_e n_0 \qquad n_e(t) = 2N - 2n_0(t) - n_i(t)$$

We can rephrase this system in terms of dimensionless variables

$$\tau = tS_0N = t/t_0 \quad K = S_i/S_0 \quad \alpha(\tau) = n_0(t)/N \quad \beta(\tau) = n_i(t)/N \quad \gamma(\tau) = n_e(t)/N$$

The evolution equations for α, β, γ are

$$\frac{d\alpha}{d\tau} = -\alpha\gamma \qquad \frac{d\beta}{d\tau} = -K\beta\gamma + \alpha\gamma \qquad \gamma = 2 - 2\alpha - \beta$$

These have initial conditions $\alpha(0) = 1 - \epsilon,\ \beta(0) = \gamma(0) = \epsilon \ll 1$

If you solve for γ and then combine the two ODE's you can find the path in (α, β) phase space by solving

$$\frac{d\beta}{d\alpha} = (K\frac{\beta}{\alpha} - 1)$$

Provided that $K \neq 1$ then the curve $\beta(\alpha)$ is given by

$$\beta = \frac{1}{1-K}(\alpha^K - \alpha)$$

The evolution of the system can then be fully described in terms of a single variable $\psi = \alpha^{-1}$

$$\frac{d\psi}{d\tau} = -\frac{1}{\alpha^2}\frac{d\alpha}{d\tau} = \frac{\gamma}{\alpha}$$

$$\frac{d\psi}{d\tau} = 2\psi - \frac{1}{1-K}\psi^{1-K} - (2 - \frac{1}{1-K}) \tag{6.4}$$

We do not know if a general closed form solution exists for this equation, and so we have mainly worked with numerical solutions instead. However there is a special case, when K = 1/2, in which equation 6.4 can be transformed into a linear equation and solved exactly.

$$\text{For } K = 1/2, \qquad \psi(\tau) = (Ae^{\tau} + 1)^2 \ \text{ where } A = \sqrt{\frac{1}{1-\epsilon}} - 1$$

This corresponds to a density evolution of

$$n_0(t) = N(Ae^{S_0 N t} + 1)^{-2} \tag{6.5}$$

$$n_i(t) = 2NAe^{S_0 N t}(Ae^{S_0 N t} + 1)^{-2} \tag{6.6}$$

This happens to be a reasonable approximation to the evolution of the helium plasma created in CTIX with its value of K = 0.57 based on the calculated cross sections. [figure showing evolution curve in (n_0, n_i) phase space] [figure showing n_0, n_i, n_{ii}, n_e as function of time for typical CTIX plasma parameters]

Accelerator Region Model Because the neutrals are not effected by the electromagnetic fields that accelerate the ions, the slow moving neutrals don't have enough time to make it into the accelerator section during the acceleration of the CT plasma. The absence of neutral helium simplifies the evolution equation for the singly charged ions while they are being accelerated.

We will now consider the evolution of the ion density with respect to a new time variable $t' = t - t_a$ where t_a is the time the fluid element has just entered the acceleration section. The initial condition is $n_i(t' = 0) = N_i$ which is the final ion density $n_i(t_a)$ using the formation region ionization model.

Because some doubly charged ions were created in the formation region, the accelerator initial condition for electron density is $n_e(t' = 0) = N_e = N_i + 2N_{ii}$, again using the formation model to find the doubly charged ion density at the time of entering the accelerator $N_{ii} = n_{ii}(t_a)$. The system evolves according to:

$$\frac{dn_i}{dt'} = -S_i n_e n_i \qquad n_e(t') = N_e + N_i - n_i(t')$$

which can be stated more compactly as

$$\frac{dn_i}{dt'} = -S_i n_i (2(N_i + N_{ii}) - n_i(t'))$$

Restated in terms of a few dimensionless variables,

$$\tau' = t' S_i N_i \qquad R = N_{ii}/N_i \qquad \beta(\tau') = n_i(t')/N_i$$

The evolution equation becomes a logistic equation:

$$\frac{d\beta}{d\tau'} = \beta^2 - 2(1 + R)\beta \qquad\qquad \beta(0) = 1$$

This can be solved to give an exact solution of the ion density evolution in the accelerator region:

$$n_i(t') = 2N_i(1+R)[(2R+1)e^{2S_i(N_i+N_{ii})t'} + 1]^{-1}$$

6.5 Conclusions

As diagnostic, a Doppler spectrometer has some unique advantages, and certain limitations that are worthwhile to take into account when planning an experiment in this field.

Unfortunately this effect also puts some constraints on the usefulness of higher Z impurities for visible spectroscopy with our plasma. For a plasma with a moderate electron temperature, there will be a highest charge state that can be obtained from electron impact ionization. For example, consider Ar V (Z=4) which is the most strongly charged argon ion that can be created in a $T_e = 100$ eV plasma. If recombination is negligible, then the Ar V will persist until the plasma discharge is complete. This terminal state has bound electrons, unlike fully ionized helium, and so can be made to emit visible light.

The difficulty is that because the excitation and ionization energies are comparable, Ar V only emits very dimly in the visible. If there is not enough energy to ionize, then there is not enough energy to excite. Attempts were made to measure visible line emission of argon ions on the CTIX plasma with no real success so far. The best results were with helium, and in spite of its limitations, the data was very revealing about the basic plasma physics.

6.6 Future work

Plans are underway to improve these Doppler measurements with a new spectrometer, and allowing better optical access using periscopic mirrors placed within the ports on the accelerator

section. The goal is to observe the red shifted light from only the plasma that has passed the port and is accelerating away from it.

Solved for ion velocity this is

$$v = c(1 - \lambda/\lambda_0)$$

$$I(\lambda, t) = \frac{1}{\sigma\sqrt{\pi}} \int_0^L I(z, t) e^{-(\lambda - \lambda_C(z,t))^2/\sigma^2} dz \tag{6.7}$$

The Doppler shifted center wavelength of line emission from the fluid element at (z, t) is

$$\lambda_C(z, t) = \lambda_0(1 - \frac{v(z, t)}{c})$$

During this process visible light is also emitted when electrons collide with neutrals or ions and exchange an insufficient amount of energy to ionize them. For example, the line emission of neutral helium at $\lambda = 5876$ Angstroms requires a bound electron to be excited from the impact of a plasma electron to an energy of 23.073 eV above the ground state before it can fall down to a lower energy level and emit the photon that we measure. However a bound electron in the ground state of He I can be ionized if it receives an energy of 24.48 eV or more from a collision with a plasma electron. Then the resulting singly charged He II ion has a similar set of possibilities. Its one remaining bound electron can be excited to 51.01 eV above the ground state, and then emit a photon at $\lambda = 4686$ Angstroms,which we then measure with our Doppler spectrometer. Or, that last electron can be liberated from the atom with just 54.403 eV of incident energy, leaving a fully ionized helium nucleus.This helium nucleus, or α particle, has no electrons in a bound state and so it does not emit any line radiation. Because the excitation and ionization energies for most atoms are quite comparable,if a plasma has an electron population that is hot enough to cause visible line emission from a species, then in general, it will also have enough energy to ionize that species into the next higher charge state. This very simple model gives an indication of how quickly the Helium

II state will become extinct under reasonable conditions, and can thereby tell us how long of a time we can expect to observe light emission from the singly charged ions. Once there are no more He II ions left in the system, there will be no more light from the $\lambda = 4686$ spectral line with which to make Doppler measurements.However, there is reason to consider a more accurate ionization model where n_i depends on axial position and time, and take into account what we know about the plasma velocity in order to make a comparison of the experimental Doppler measurement of average velocity and an independent evaluation of the same quantity using the right hand side of equ. 4 and our current understanding of the dynamics of CTIX. So the next task is to consider the effect of ion acceleration relative to a nearly stationary cloud of neutrals, while ionization is occurring.

Constant Temperature Model with Particle Motion In order to account for the ...

Adiabatic Expansion Model Now consider ...If the intensity of light emission due to the specified line transition is proportional to the ion density $I(z,t) \propto n_i(z,t)$ then this reduces to

$$v_{ave}(t) = \frac{1}{N(t)} \int_0^L n_i(z,t) v(z,t) dz \qquad N(t) = \int_0^L n_i(z,t) dz \tag{6.8}$$

The weighting function is the normalized density of the ion species we are interested in observing (He II), as a function of axial position and time.Justification of simple proportionality between local number density of charge state and brightness of line emission can be made by looking at the ratio of excitation to ionization cross sections and will be discussed in the following section.

$$\beta = \frac{1}{1-K}(\alpha^K - \alpha)$$

$$\frac{d\psi}{d\tau} = 2\psi - \frac{1}{1-K}\psi^{1-K} - (2 - \frac{1}{1-K}) \tag{6.9}$$